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Fracture Toughness: Evaluation of Analysis Procedures to Simplify JIC Calculations

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To the Graduate Council:

I am submitting herewith a thesis written by Thomas Joseph Battiste entitled "Fracture Toughness: Evaluation of Analysis Procedures to Simplify JIC Calculations." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

John D. Landes, Major Professor

We have read this thesis and recommend its acceptance:

J. A. M. Boulet, Archie Mathews

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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to Simplify J_{IC} Calculations

A Thesis Presented for
The Master of Science Degree
The University of Tennessee, Knoxville

Thomas Joseph Battiste
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Abstract

The purpose of this study is to determine if there is an alternative analysis method that can provide an estimate of fracture toughness for specimens that failed to meet all of ASTM E 1820 requirements. This study will look at three alternative analysis methods and evaluate each method's ability to accurately and easily estimate the elastic-plastic fracture toughness. The standard method of analysis is long and complicated which leads to a number of validity requirements that many tests fail to meet. The objective is to find an easier and reasonably accurate estimate of elastic-plastic fracture toughness.

This study has shown that there are two useful means of directly measuring the toughness from the load versus displacement record. It has also shown that there is a method of substituting a linear regression for the power law regression which yields good estimates of fracture toughness. All three methods have been estimating J_Q which is a provisional measure of elastic-plastic fracture toughness. The first direct method uses an integral of the area up to the maximum load point to acquire the J_Q. The second direct method uses a conversion of the linear elastic fracture toughness which only uses the crack growth and the maximum load from the load versus displacement record. The final method substitutes a linear regression of the two J-R points on either side of the J_Q line to determine the J_Q point.

Each alternative analysis was able to acquire J values with varying degrees of accuracy. The linear substitution was the most accurate. The first direct method using an area integral tended to over predict the true J value. The second direct method using a conversion formula had a tendency to under predict the true J value. None of these

methods could substitute for the ASTM standard; however, each provided a usable estimate of elastic-plastic fracture toughness.

Nomenclature

a	crack length
A_{MAX}	total area under the load displacement curve to maximum load
B	specimen thickness
B_n	net section thickness
b_o	uncracked ligament length
C1	coefficient for J-R curve fitting
C2	exponent to J-R curve equation
E	modulus of elasticity
$F(a/W)$	polynomial based on the crack length divided by the width
J	path independent contour integral
J_{MAX}	J determined using area under load displacement curve
J_Q	provisional J_{IC} fracture toughness
J_{Q2pts}	provisional J based on two points regression
J_{IC}	critical path independent contour integral
K	crack tip stress intensity factor
K_Q	provisional K_{IC} fracture toughness
K_{IC}	critical crack tip stress intensity factor
P	load
P_{MAX}	maximum load
P_Q	load to force a crack to grow
W	specimen width
v	displacement
Δa	crack growth increment
η	coefficient in J calculation dependent on specimen geometry
σ_y	effective yield stress
σ_{ys}	yield stress
V	Poisson’s ratio

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Chapter 1: Introduction

A great deal of structural engineering work goes into avoiding failures. This entails a large amount of analysis. Stress analysis is one of the first techniques a student learns and is one of the most common actions a structural engineer will perform. The problem is that for some parts this is not enough. Some parts fail at stresses lower than those accounted for by the typical analysis of failure by yielding. These failures are often caused by defects not accounted for by yielding. It is these failures that fracture mechanics attempts to predict and avoid. The goal is to know how much stress it takes for a crack to grow. From this stress level a critical stress level can be determined so that a structure can be safely used. The key to predicting this critical stress level is that fracture mechanics can relate stress, crack size and shape, with the fracture toughness of a material. For this to work stresses have to be calculated, and the inspection process has to be able to determine a certain size of defect so that the fracture toughness can be applied appropriately [1]. Fracture toughness is simply the material's ability to resist growth of a crack [2]. Quite often the difficultly arises in determining the fracture toughness of a material.

Fracture mechanics uses two progressive steps to attempt to accurately characterize a material; linear elastic analysis and nonlinear elastic-plastic analysis. Purely elastic problems are called linear elastic fracture mechanics (LEFM). Linear elastic fracture mechanics is generally used on low toughness materials where crack growth occurs with minimal unrecoverable damage. These materials tend to have high yield strength or be very brittle. Elastic-plastic fracture mechanics (EPFM) as the name implies, attempts to include the unrecoverable damage that occurs ahead of the moving crack in the amount of energy resistance of the material [1]. This is generally used on medium to low strength materials, and materials at elevated temperatures. EPFM tends to be the more complicated of the two methods and thus creates more difficulty in determining a fracture toughness value. As with stress analysis, the introduction of plastic damage adds a number of conditions that makes it more difficult to get a viable answer. This is easier to see when the different techniques are discussed in detail. As with yield strength, fracture toughness is only determined through a standard test method. These test methods, such as ASTM E 1820 [3], include the details for finding the fracture toughness of a material including all the conditions and restrictions for validating the results. Some of these validating conditions are being called into question for being excessively restrictive [4], and some materials, such as the ones in this study, are just incapable of meeting all these conditions and need further work to develop usable results.

This study will look at two compact tension J_{IC} test sets, using two alloys. Due to the materials being proprietary, these two materials will be labeled A and B. These materials were tested for a large company by an independent testing lab according to the ASTM E 1820 test procedure. The analysis for this study was done via a computer program. The baseline analyses were done with a Matlab program that does the computations required by the ASTM E 1820 procedure. The test sets had a large number of invalid tests, so alternative analysis procedures were attempted and conducted by using Excel to process the raw load versus displacement data.

Some materials, such as the two in this study, cannot meet all the validating conditions. These validating conditions were constructed from the empirically derived formulas used to portray the crack growth. Because the formulas cannot perfectly represent all the possible variations in fracture mechanics, it will be necessary to find alternative analysis methods in order to more accurately represent the fracture toughness of a material. The goal of this study is to look at two materials and see if there is a possible alternative analysis method that yields representative fracture toughness values. This study was done on the two large test sets, one for each material. The specimen testing was all conducted by an outside laboratory according to the ASTM E 1820 test procedure. The first job was to analyze all the tests according to the standard, so that the valid tests could be used as the control for the alternative analysis methods. Then the test sets were analyzed using three different analysis methods; the Landes-Pehrson method, the J from K method, and the two points method. Each of the three alternative analysis methods will be compared to control sets to evaluate the accuracy of each. Since each of these three alternative analysis methods can only estimate the fracture toughness value, the accuracy can only be compared to the valid tests. This makes it important to understand why so many tests were invalidated and how each of the alternative methods deals with the invalidating issue.

Chapter 2: Background

Fracture mechanics is used to determine the effect crack-like defects will have on the structural stability of any structure [5]. The goal of fracture mechanics analysis is to find the exact amount of stress a part will withstand before the defects grow to failure. This amount of stress is used to determine the minimum load or critical defect size that will cause the analyzed part to fail [1]. Determination of the fracture toughness property is the first step in calculating the critical values for failure.

For parts that likely have a crack-like defect or are deemed critical parts that must not break, there is a procedure for determining the critical stress levels. For these critical parts a stress analysis is conducted as would usually be done for all parts in a mechanism. This study will focus on the crack growth portion of the procedure aimed at reducing failures in critical parts. The first step is to find the orientation of the crack-like defect. The direction of the crack relative to the loading determines the mode of fracture. This is one of the keys to determining how damaging a defect is. If the loading is perpendicular to the crack, it is mode I [6]. Modes II and III are shear modes, in plane and out of plane respectively. Examples of the modes of fracture are shown in Figure 1, which is in the appendices along with all the other figures and tables. The standards are written for test specimens loaded in mode I as this is typically the one more people are concerned with. The next step is to determine the form of the loading. For a mode I crack, the typical loadings are tension or bending. Tension is the more common of these loading types for testing and is the only loading used in this study.

The way the material deforms determines the form of the analysis. For materials that exhibit mostly elastic deformation prior to failure, linear elastic fracture mechanics

(LEFM) provides a good prediction of the crack growth. LEFM is a relatively simple and direct method for finding fracture toughness that is based on crack tip stress intensity parameter, K. This will not work for finding the fracture toughness of a material that exhibits significant plastic deformation. For materials that deform plastically prior to crack growth, nonlinear elastic plastic fracture toughness (EPFM) is used. To encompass the nonlinear effects of plastic damage, EPFM uses a more complex analysis along with a different set of parameters. In the ASTM standard, the nonlinear plastic damage is accounted for with an integral of the load versus displacement record. This necessitates that a new parameter be used. This parameter, J, is the path independent contour integral of analysis of cracks developed by Rice [7]. A significant number of materials deform in a nonlinear or plastic manner, which means that a J toughness value is often required. There is a problem with this. There are a large number of unique load displacement paths for plastic deformation. These different paths are more difficult to encompass and bring more complications that are not always within the scope of the standard. A quick review of the linear test method should help focus on the issues with elastic-plastic fracture mechanics.

Materials that grow cracks primarily by elastic deformation, such as high strength steels and brittle materials, are handled with the crack tip stress intensity factor K. The standard ASTM E 399 [8] can only deal with a very limited amount of nonlinear damage. The plastic damage zone must be much smaller than the dimensions of the specimen otherwise the crack growth cannot be approximated linearly. Linear methods of analysis are by their very nature, generally easy to handle.

The crack-tip stress intensity factor is found with the maximum load and the crack length of a given specimen. At the failure point the value of the crack-tip stress intensity factor is deemed critical and is known as the K_{IC}, a fracture toughness value. The K_{IC} value is measured by a standardized test method which for linear elastic fracture toughness is ASTM E 399 [8].

For single specimen analysis which is all this study used, a clip gage is used to estimate crack extension from the crack-tip opening displacement. These specimens, like all fracture specimens, must be fatigue precracked so that the crack is sharpened. The specimen is loaded through the maximum load it can maintain and begins to shed load as a result of the crack extension. The test analysis begins when this point is reached.

A record of the load and the displacement is used in the analysis to attempt to find the K_{IC} of the material. The starting point is determining P_Q which is the applied force to grow a crack. An offset line is drawn parallel to the linear section of the load-displacement record, and the intersection of this offset line and the load displacement record is P_Q. P_{MAX} is found by taking the maximum sustainable load. P_Q must be within 10 percent of the maximum load, P_{MAX}. This process is detailed, including graphically representation, in ASTM E 399. The next step is to determine a preliminary K value labeled K_Q.

If this K_Q meets all the validity requirements, then it will become the K_{IC}. The formula for K_Q is given as

$$K_Q = \{P_Q * F(a/W)\} / \{B \sqrt{(W)}\} \qquad \{1\}$$

B is the thickness of the specimen, W is the width, and F(a/W) is a polynomial based on the crack length divided by the width. P_Q is the only piece of data from the load displacement record. F(a/W) is based on the original crack length and as such is a function of measured specimen geometry, as are B and W.

Once a K_Q value is found, a series of validation requirements are needed to verify that the test result meets all the constraints and that the K value found is the critical K_{IC}. The first requirement is specimen size. Since the test method was formulated in plane strain, the specimen must be of sufficient thickness and possess the necessary crack length for the K values to remain in plane strain. This is done by comparing the thickness and crack length to confirm that they both meet the following size limitation:

$$2.5\ (K_Q\ /\ \sigma_{ys})^2 < B \text{ or } a \qquad \{2\}$$

Where K_Q is the test's K value and σ_{ys} is the yield strength.

The K_{IC} test method and analysis are significantly different from the test analysis procedure for the elastic-plastic fracture toughness testing. LEFM testing uses a direct and simpler analysis then EPFM testing. It is helpful to see what similarities exist between the two test methods. Both test methods use the same specimen and loading apparatus. They are both fatigue precracked and the geometry of each specimen is carefully measured. Both have validation conditions; however, the EPFM analysis is more involved. The testing procedure is different as is the analysis.

While the test specimen and associated apparatus are the same, the way in which they are used is different. To account for the nonlinear plastic damage the standard, E 1820, uses a construction with regression and conditionals to form the J-R curve. It then requires more constructions to find the provisional J, also known as J_Q. Then more validation tests are used to ascertain whether the J_Q is or is not the critical J_{IC}. These increased calculations and test steps increase the potential for error, which is one reason for this study. This has been demonstrated in a paper by Landes and Brown [4].

The compact specimen used in both methods of fracture toughness testing is loaded through clevises, but the loading is not continuous. The specimen is subjected to numerous loading/unloading cycles. From this process the crack growth for each cycle is measured. This is shown in the load displacement record in Figure 2. These must be done often as the measures of crack growth and the resistances to crack growth are needed in a very narrow region and are not recoverable if this region lacks data. These load/unload cycles will be used to develop a J-R curve. The J-R curve is a crack growth resistance curve. There is a procedure for acquiring the J-R curve that entails finding the J at each load/unload cycle and the associated crack extension. This incremental approach is the standard method of utilizing the J-integral. The formula for the J integral is

$$J = (\eta / B_n b_o) * \int P \, dv \qquad \{3\}$$

where η is a coefficient, B_n is net section thickness, b_o is initial uncracked ligament length, P is load, and v is displacement. The net section thickness, B_n, is used because many compact tension specimens used for EPFM are side grooved, as shown in Figure 3, to ensure the crack grows in a consistent plane of the specimen and with a straight crack front. Often the crack front will be so convoluted that is does not represent the conditions of the J fracture toughness. Measuring and controlling crack growth is one of the validation issues that can be a problem; however, side grooving tends to reduce the number of tests invalidated by convoluted crack growth. Controlling and measuring the crack front comprise the majority of issues with validating test results.

At this point in the J-R curve construction the curve is only a series of points. The chart, as shown in Figure 4, has qualification lines drawn on it. The first is a construction line with a slope of

$$J = 2\ \sigma_y\ \Delta a \qquad \{4\}$$

where σ_y is the effective yield stress which is the average of the yield and ultimate strengths, and Δa is the change in crack length. This construction is then offset three times. The first is a minimum exclusion line starting at 0.15 mm crack extension. Only data to the right of this line will be used. The next is the maximum exclusion line which is drawn at 1.5 mm crack extension and only data to the left of this line will be used. These boundaries ensure that the crack growth has not exceeded the measurement limits of the specimen. The third line is the intersection line also known as the J_Q line. This line starts at 0.2 mm. The intersection of this line and the J-R curve will become J_Q.

Since at this stage the J-R curve is only a series of points, it will require a regression to get the point of intersection with the offset line. The regression is a power law regression of the form

$$J = C_1\ (\Delta a)^{C_2} \qquad \{7\}$$

where C_1 and C_2 are a constant coefficient and exponent respectively for regressions and not based on measurements. Following this regression the graph should look like Figure 4. It is important to note that there are a minimum number of data points required. It takes at least one J-R data point between the lower exclusion line and the intersection line, plus at least four J-R data points between the intersection line and the maximum exclusion line for the regression to be valid. This is due to the mathematics of regression. If there are not enough data points then the regression is no longer a power law and becomes a simpler regression, i.e. polynomial or linear. From this regression curve and the intersection line the J_Q can easily be found. As the above conditions show there are a number of results that could lead to an invalid test result. Some of these may be too restrictive and thus eliminate useful results.

Recent work by Landes [9] has shown that some of the rules used for fracture toughness testing are not crucial for acquiring viable results. In this paper Landes applies ASTM E 1820 [3] to a set of tests. This test matrix, the Euro test set, is a large number of tests that individually are valid; however, when the ASTM criteria are applied to the test set as a whole there were no valid fracture toughness results. Also, this paper shows analysis where some of the criteria eliminate individual valid tests, which arbitrarily degrade the analysis process by lowering the number of data points. A companion paper [10] goes on to use ISO test method 12135:2002 [11] to find fracture toughness values from this test set. This companion piece also showed that a number of the rules were questionable regarding the process of finding a good fracture toughness value. Typically the specimen size requirement was the rule that was questionable. Large specimens that met the size requirement were compared to smaller specimens that did not meet the requirement. The results were that both sizes yielded the same fracture toughness values, indicating that the size requirement may be too strict. This work has led to a ballot for revision of ASTM E 1820 in order to relax the size requirement by approximately a factor of two.

From this potential change in the standard other rules may prove to be excessively confining and not critical when attempting to find fracture toughness values. Specifically these test sets lack the required number of J-R pairs in the qualified region for full acceptance by ASTM, but useful data can still be acquired by the process described in this paper. This is important to note because the cost in terms of both money and time for fracture toughness testing is high compared to standard tensile or even typical fatigue tests. This study will look at alternative analysis methods to deal with the lack of data points and compare these values to valid tests.

Chapter 3: New Analysis

The standard method of finding elastic-plastic fracture toughness has a number of conditions that may invalidate the test results, which means that the values are no longer accurate representations of the fracture toughness of the material. To predict and avoid failures due to crack-like defects, accurate fracture toughness values are necessary, so an inaccurate representation of fracture toughness is problematic. To solve this problem, new analysis techniques need to be used in order to find representative values of fracture toughness. This study purposes three such new analysis techniques. These analysis techniques use the same test results as the standard, ASTM E 1820. The first technique is the Landes-Pehrson which goes all the way back to the J integral and uses a direct integration to determine the fracture toughness. The second technique is the J from K method which is a conversion of K fracture toughness values into J values found within the ASTM E 1820 standard. The third technique is based on a simplification of the standard in which a linear regression is substituted for the power law.

3.1 Landes-Pehrson

The first technique is the Landes-Pehrson method [12]. This method starts with the load displacement record, exactly like the ASTM E 1820 standard; however, it uses an integral up to the maximum load instead of integrating to each load/unload cycle to build a J-R curve. It estimates the J_Q point directly from the load versus displacement record. This reduces the analysis steps by eliminating a construction procedure which should reduce the possible number of mistakes.

To start analyzing for elastic-plastic toughness utilizing the Landes-Pehrson method, load displacement data from a compact tension specimen, shown as Figure 3, must be used. This must be tested according to a standard test method to acquire viable fracture toughness values. From the ASTM E 1820 [3] test method the load-displacement record will include a number of unloads that the analysis uses to predict crack growth. These unloads are not used so they must be removed. This will produce a curve of monotonically increasing displacement. At this point it helps to look at the energy release definition that is used to find the elastic-plastic toughness:

$$J = (\eta / B\ b_0)*(\int P\ dv) \qquad \{8\}$$

where P is load, v is displacement, B is width, b_0 is uncracked ligament, and η is a coefficient. J is the value of fracture toughness. The Landes-Pehrson method uses a direct numerical integration for the integral in Equation {8}. This is shown in the formula

$$J = (\eta\ A_{MAX}) / (B\ b_0) \qquad \{9\}$$

The only difference between {8} and {9} is that the integral in {8} is now the area of the load displacement chart up to the onset of maximum load as shown in Figure 5. The ASTM standard for elastic-plastic fracture mechanics was developed in the 1970s when computer data acquisition systems were unable to capture enough data points to accurately represent the load displacement curve via distinct load and displacement values. The way the ASTM committee handled this difficulty was by incrementally estimating the crack growth from unloading slopes and finding incremental J values. This means that the standard constructs an R curve for each test. This is one of the main differences between the two methods. The Landes-Pehrson method uses a continuous J, integrated from a single point, and E 1820 utilizes a regression curve for interpolation. Thus the difficulty of the Landes-Pehrson method is in finding the provisional critical fracture toughness value, J_Q. This difficulty is brought about by the fact the standard builds an R curve and the Landes-Pehrson method only finds a single point along the R curve that becomes the J_Q.

From the standard, J_Q has to fulfill a number of conditions to become the critical value. To ensure that the value of J_Q is consistent in the Landes-Pehrson method, the maximum load point is used in its determination. This means that the load displacement curve is integrated up to the first instance of the maximum load. The resultant of this integral is the J_{MAX}, for that test. When Pehrson was testing this method he found that the size of a specimen had an influence on the result of his J_{MAX} which needed correcting to make them match the value of each given material. This size correction was

$$J_Q = \sqrt{(W_{ref})} * J_{MAX} \qquad \{10\}$$

with W_{ref} in millimeters, and in his case, it was the 50 mm size specimen that had J_{MAX} values, which matched the J_Q values of the steels that he was analyzing. All of the specimens tested in this study were 25 mm wide, and after comparing the valid test results to the Landes Pehrson results the 25 mm width specimen did not need to be size corrected.

3.2 J from K

The second technique is from ASTM E 1820. In this standard there is a method for converting elastic-plastic fracture toughness values into linear elastic fracture toughness values. In this case the tests were reanalyzed for linear elastic fracture toughness which yielded K values. These K values were then converted using the inverse of the conversion method in the standard. This allows the use of the easier and less restrictive K_{IC} analysis while finding an elastic-plastic fracture toughness value.

ASTM E 1820 has a method for converting elastic-plastic toughness into linear elastic toughness. It is needed since a number of materials have only elastic-plastic deformation during testing or are designed for linear elastic loading in the structural application. This is a simple procedure but it comes with conditions. The first issue is that going to J from K means that the converted value does not account for plastic damage. This means that it will be conservative, which is not necessarily a problem, but is not ideal. Going from J to K is a problem in that the J value has some plastic damage which the K value does not represent. This is correctable since the analysis for K values is much easier than that for J values. If the raw data is available then the test can be reanalyzed to acquire a true K value. For this study the raw data was available and was used to find a K value. This K was then converted to a J value.

The procedure for the conversion is a single formula given by Equation {11}. The only extra data required are the elastic modulus and Poisson's ratio, which come from a tensile test or can be found in a material database.

$$J = (K^2)*(1- v^2) / E \qquad \{11\}$$

where E is Young's modulus, v is Poisson's ratio, and K is the linear elastic stress intensity factor from ASTM E 399 (8). This is a good alternative for materials that undergo little plastic damage prior to crack growth. The K value is easily obtained and is given by

$$K = \{P_{MAX}\, F(a/W)\}/\{B\, \sqrt{(W)}\} \qquad \{12\}$$

where P_{MAX} is maximum load, F(a/W) is a polynomial based on crack length divided by total width found in the standard, B is the thickness of the specimen and W is the total width of the specimen. This information is easily found from the load displacement record and the measurements of the specimen. This is then used in the conversion formula to acquire a J value. This is most useful in comparing materials that demonstrate different failure types. This study noted that the amount plastic damage is inconsistent from test to test, so this type of comparison was tried.

3.3 Two Point

The third alternative analysis technique is the two point method which is a simplification of a task in the standard E 1820 test analysis procedure. In the standard analysis procedure there is a series of steps for using a power law regression on the calculated points for the J-R curve. These are altered to allow a simple two points linear fit instead as shown in Figure 6. This reduces the number of conditions that are necessary for the power law, while matching the results a power law would have if there were only two points.

The two point method is devised to substitute a simple linear analysis into the nonlinear power law regression for tests that only have fewer than the required five points in the qualified region. The basis for this method comes from looking at a power law regression of two points, which is a straight line. ASTM E 1820 protocol is followed and only the regression is altered. From the raw data each load/unload sequence is analyzed to acquire J-R pairs which are charted like Figure 6. From this chart the exclusion lines are drawn as is the J_Q offset line given by

$$J = 2\ \sigma_y\ (\Delta a - 0.008\ \text{(inches)}) \qquad \{13\}$$

Since it is the intersection of this offset line and the power law regression that determines J_Q, a power law regression of the two J-R pairs on either side of this offset line are used to find a linear point of intersection. This intersection is labeled J_{q2pts}. This is especially useful in tests where the crack grew in an unstable manner, which in fracture mechanics is labeled a pop-in. This common occurrence typically invalidates a test and yields a misshapen J-R curve that cannot be used for the construction procedure required in ASTM E 1820. Since a J-R curve is typically concave down, the use of a line between any two points on said curve should be conservative since the curve should have J_Q values above the J_{q2pts} values. This is important because the occurrence of a pop-in indicates that the material may not be as tough as expected. This technique needs to be compared with valid ASTM E 1820 tests to see just how conservative the J_{q2pts} values are. One problem with this technique is that it still borrows the J_Q offset line from the standard, E 1820. This can be problematic in tests where unstable crack growth is observed since it can be difficult to achieve a J-R pairing on either side of the offset line. The gap between the exclusion and J_Q offset line in the standard is 0.002 inches which is a very narrow band of crack growth in which to get an unloading sequence. Further work looking into expanding the qualifying region could help with this problem and may lead to fewer tests being invalidated, which may negate the need to use techniques such as these.

Chapter 4: Results

Elastic-plastic fracture toughness tests were conducted on two materials using ½ T geometry specimens. The ½ T specimens are an ASTM standard specimen also known as a compact tension specimen that is ½ of an inch in width. The first step was to analyze the raw data to find all the valid tests. These tests provided only a few valid test results, so alternative analysis methods are examined to find good estimates for the fracture toughness. Both test sets have a combined 171 tests with 104 of them for material A and 67 tests for material B. These were all tested according to E 1820 which returned load versus displacement curves such as the ones in Figures 7 and 8. These load versus displacement curves were analyzed and the J-R curves similar to the ones in Figures 9 and 10 were the result. These tests yielded only eight valid tests for material A and 20 for material B as shown in Tables 1 and 2. This means only 16 percent of all the tests were valid and their results are given in Tables 1 and 2. These valid tests were then reanalyzed using each of the three alternative analysis methods. These results are summarized in the three comparison graphs, Figures 11, 12, 13. The results of each reanalysis were added to Tables 1 and 2. Each figure compares an estimation method with the values from the standard. The line on each graph represents the optimum solution of the estimated value equaling the ASTM value for each specimen.

The valid test result versus Landes-Pehrson comparison graph labeled Figure 11, shows the tendency for this estimation method to over predict. It also demonstrates the large amount of over prediction. The distance from the optimal line shows how far each prediction is off from the standard. The error in the prediction goes from 3.5 percent under to 93 percent over for material A and 7 percent under to 39 percent over for material B as seen in Tables 1 and 2. Approximately half of the tests are on the optimal line which says that this technique may be used and with further development might be made more accurate. Another thing this graph shows is that the lowest values of J are about half of the highest values for both materials. The large spread in J values shows that both materials have a significant scatter. Even though both materials are from the same family of metals, material B is significantly tougher than material A.

The standard versus J from K comparison graph, Figure 12, shows that material B is typically under predicted and material A is both under and over predicted. Material B estimates are often severely under predicted. For material A the error in the estimate for fracture toughness as compared to the standard E 1820, shown in Table 1, varied from 43 percent under to 36 percent over. For material B the error in the estimate for fracture toughness, shown in Table 2, varied from 2 percent to 35 percent under. The under predictions of elastic-plastic fracture toughness were expected as the K values used in this analysis do not take plastic deformation into account. The degree of under prediction was not expected. The over predictions from the J from K method for material A were completely unanticipated as this method should only under predict the true J value. The over predictions might be a product of the unstable crack growth causing the J-R data points to shift right, which will cause the J-R curve to be lower then if there were no unstable crack growth. The two under predictions are so far from the standard that it is difficult to be sure of the cause, especially since the rest of material is over predicted. If all the predictions had been under the standard values then at least the predictions could be used as a lower bound value for the fracture toughness.

The two points comparison graph show a close agreement between analyses J_Q values. Figure 13 shows all eight of the material A specimens touching the optimum line, and all but two of the twenty material B specimens touching the optimum line. The two material B specimens that are not touching happen to be on either side of the line and appear to be about the same distance from the line. With such good agreement, it is likely that the error is caused by the unstable crack growth and there is little that can be done to fix this material issue. Because there is such good agreement, the two points analysis method was extended to all the tests in both tests sets to see how well the method works on invalid tests and to determine what the elastic-plastic fracture toughness is for both materials. This is shown in Tables 3 and 4 for materials A and B respectively. The agreement between the two points and the E 1820 values remains good even though the standard test analysis had to be limited to the J_Q and the power law regression was done regardless of how many J-R data points were available.

Chapter 5: Discussion

For both materials A and B all the tests were analyzed according to ASTM E 1820. From this analysis only a limited number were valid, and the valid tests results are shown in Tables 1 and 2 for materials A and B, respectively. The valid tests were then reanalyzed using the three alternative analysis methods and the results were added to the tables. The column next to each alternative's J value shows the percent error as compared to the standard J_Q value for that specimen. The E 1820 J_Q values and the alternative analysis J_Q values were then used to make comparison graphs shown as Figures 11, 12, and 13 for each alternative analysis method in order to visualize how close each alternative was to the standard.

From the tables it was evident that the two points analysis method was the closest to the E 1820 values. The next step was to run the two points analysis on the complete tests sets, which is shown in Tables 3 and 4. This shows a similar trend to the valid tests and provides values for tests that lack enough data points for the standard. The invalid tests were analyzed to the point of acquiring a J_Q value even though they were not valid in order to compare to the two points method. The two points method was nearly as close at predicting the J_Q for the invalid tests as it was the valid tests, so it could and should be used for estimating so long as there are the two J-R data points in the qualified region. For cases where there are not two J-R data points the Landes-Pehrson and the J from K could be used to bracket the J value. This would be similar to plasticity analysis where one method produces the upper bound and the other method obtains a lower bound.

The Landes-Pehrson and the J from K analysis methods were able to produce J_Q values, but they were not as accurate as the ASTM standard. This inability to accurately predict the J_Q can be traced to how each method deals with the raw data. There was some indication from the load versus displacement record of a lack of stiffness in the test frame or load train. The initial portion of the P-V records curve back as if the crack had shrunk as load increased, which is not possible. The fact that the P-V curves also showed skips in the curve indicates unstable crack growth which definitely contributed to the lack of J-R data points in the qualified region. Both of these phenomena are shown in Figures 7 and 8. This unstable crack growth is likely the main reason many of the tests were invalid. As this is a condition of the material, there is no way to eliminate this problem, and alternative analysis methods need to be developed to deal with this.

Chapter 6: Further Work

Each of the three alternative methods is an adaptation of some earlier work. The Landes-Pehrson method was started from the J-integral similar to the ASTM standard; however, it is a new concept in using the J-integral and it can be developed further. Finding a more consistent upper limit of integration for acquiring the J_Q point would take more test sets full of valid tests according to E 1820 in a large variety of materials to determine a better point than the maximum load point for the limit of integration. This new upper limit will likely be based on a polynomial with a number of variables including the specimen size. A useful project would be to take a large variety of valid fracture tests and attempt to find a viable method or formula for the upper limit of integration for the Landes-Pehrson method. The J from K method is from the ASTM standard with a modification. It is the reverse of the procedure in the standard, and has little that could be altered to make it more suitable as an estimation technique. This means that there is no further development to be done to the J from K technique. The two points method is a substitution of a linear regression for the power law regression in the ASTM standard. This simplifies the steps used and uses the same validity requirements from all the other steps, but is not going to be as accurate as the standard as it does not use the as much of the J-R curve to find the J_Q point. There is little that can be done with this other then to use it in parallel with the standard to help verify the results and to estimate results for invalid tests. However a good project would be to evaluate the two points method with a broad range of test materials with widely varying fracture toughness values in order to determine its effectiveness as an estimation method.

Chapter 7: Summary

The three alternative analysis methods can provide good useable estimates of elastic-plastic fracture toughness. The three alternative analyses are the two points method, the Landes-Pehrson method, and the J from K method. Each method estimates the fracture toughness using a simpler method then the standard, ASTM E 1820. All three methods proved to be much easier to use then the standard. Each has a use but none was accurate enough to be a replacement for the standard. Each method also exhibits problems related to how it estimates the fracture toughness, and these problems impact the use and accuracy of the estimate method.

The two points method proved to be the best estimation method; it works so long as there are at least two J-R points. It is not necessary for there to be five J-R points as the ASTM E 1820 standard requires. It does require that the two points are on either side of the J_Q line. Because the gap between the first exclusion line and the J_Q line is small, this is a problem for many tests. The second problem is that the further the second J-R point is from the J_Q line the larger the error in the estimate. In the case of large test sets that often can not produce J-R points; the two direct methods could be used. If some tests are, valid then these are used to calibrate the direct method. Then either the Landes-Pehrson method with its tendency to over predict or the J from K method with its tendency to under predict could be used. Calibration is done by comparing the valid E 1820 results with the results from the direct estimate methods for the same test. The goal is either reference size determination or verification of over / under prediction plus the amount of deviation. Each is useful depending upon what is being done with the result. Over predictions are useful for failure analysis by helping to indicate the maximum developed stress. Under predictions are useful for design by indicating the maximum allowable stress.

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Appendix A: Tables

Table 1: Material A valid J_Q values							
Specimen	**E 1820**	**Landes-Pehrson**	**% Absolute Error**	**J from K**	**% Absolute Error**	**Two Points**	**% Absolute Error**
1	403	435	7.9	275	31.7	394	2.1
2	253	348	37.2	340	34.2	263	3.9
3	313	510	62.6	423	34.9	314	0.2
4	210	407	93.7	286	36.4	226	7.5
5	316	444	40.6	409	29.6	326	3.4
6	321	309	3.5	182	43.1	303	5.5
7	333	505	51.7	375	12.7	329	1.2
8	308	458	48.8	351	14.0	353	14.9

Table 2: Material B valid J_Q values							
Specimen	**E 1820**	**Landes-Pehrson**	**% Error**	**J from K**	**% Error**	**Two Points**	**% Error**
1	829.29	859.91	-3.7	620.68	25.2	850.12	-2.5
2	942.45	1016.18	-7.8	738.09	21.7	966.68	-2.6
3	949.98	922.37	2.9	636.04	33.0	947.35	0.3
4	775.18	781.67	-0.8	627.49	19.1	805.10	-3.9
5	774.32	792.85	-2.4	543.44	29.8	797.25	-3.0
6	520.95	568.29	-9.1	502.20	3.6	538.23	-3.3
7	812.09	757.84	6.7	550.61	32.2	846.30	-4.2
8	615.19	857.60	-39.4	604.18	1.8	627.30	-2.0
9	788.10	811.83	-3.0	642.00	18.5	799.89	-1.5
10	685.94	648.62	5.4	556.26	18.9	692.89	-1.0
11	768.08	948.28	-23.5	637.34	17.0	788.23	-2.6
12	670.72	878.93	-31.0	594.49	11.4	681.22	-1.6
13	817.47	835.32	-2.2	598.34	26.8	834.99	-2.1
14	623.72	638.76	-2.4	515.96	17.3	640.03	-2.6
15	592.79	681.34	-14.9	489.13	17.5	595.50	-0.5
16	782.70	872.99	-11.5	630.73	19.4	796.00	-1.7
17	743.24	756.77	-1.8	555.33	25.3	762.28	-2.6
18	926.54	930.23	-0.4	603.06	34.9	957.15	-3.3
19	899.15	891.30	0.9	658.19	26.8	936.58	-4.2
20	675.53	851.39	-26.0	576.57	14.6	687.95	-1.8

Table 3: Material A: E 1820 and Two Points

Test Name	J_{E1820}	J_{2point}	Test Name	J_{E1820}	J_{2point}	Test Name	J_{E1820}	J_{2point}
B61033	300	338	C80269	311	324	D30784	198	196
B64430	310	302	C80276	No data	835	D30785	314	307
B64432	270	281	C82395	403	404	D30787	338	340
B66268	319	321	C82397	360	339	D32930	302	292
B69000	260	267	C90773	346	325	D32931	280	270
B73723	321	320	C93156	368	359	D32933	379	360
B75222	403	394	C93157	547	528	D36429	215	217
B76790	408	392	D01144	344	325	D39756	348	345
B80534	308	304	D01180	368	361	D43876	399	380
B87506	295	287	D01184	295	295	D43878	289	298
B91555	276	262	D03907	248	232	D46428	248	252
B91559	376	364	D03908	No data	No data	D46431	438	424
B95211	690	744	D03909	244	228	D57579	362	359
B98504	282	269	D03910	321	303	D57590	No data	310
C03373	260	258	D03911	No data	No data	D76666	340	345
C03376	254	264	D03912	284	276	D81540	313	323
C03377	314	314	D03914	339	317	D82716	353	341
C03378	210	226	D03915	No data	163	D94533	429	422
C16323	316	327	D03916	229	224	D96164	378	370
C51727	357	360	D11310	443	441	D96165	349	341
C52628	No data	356	D12530	383	361	E00202	318	320
C54704	363	366	D15305	363	349	E01248	308	289
C60417	381	396	D23305	264	253	E06794	384	376
C61517	310	324	D25572	317	318	E06803	339	329
C61518	352	341	D25573	180	182	E06804	246	234
C63362	259	272	D25696	363	326	E06805	276	277
C66164	310	325	D25697	No data	167	E06806	254	254
C68674	212	233	D25724	318	318	E06807	277	274
C68675	244	232	D25729	334	330	E06808	262	253
C68689	311	313	D26851	257	253	E12662	365	363
C68690	297	296	D28057	341	330	E14414	383	378
C70299	297	303	D28075	447	427	E14415	284	280
C71321	329	324	D29358	309	354	E18094	307	316
C78049	332	329	D30780	216	208	E26634	389	369
C79396	357	354	D30781	299	296			
C79399	295	292	D30783	No data	361			

Table 4: Material A: E 1820 and Two Points						
Test Name	J_{E1820}	J_{2point}		**Test Name**	J_{E1820}	J_{2point}
B29801	425.53	416.51		C49286	817.47	834.99
B32331	912.95	943.79		C51719	937.50	963.54
B32332	829.29	850.12		C66162	822.12	848.40
B43039	942.45	966.68		C80272	347.71	375.64
B43040	718.99	744.01		C80275	717.20	773.57
B43492	949.98	947.35		C90771	752.31	729.03
B43493	698.45	790.31		D01146	818.77	852.02
B44238	855.29	911.24		D02766	629.92	647.83
B44239	775.18	805.10		D02768	658.11	645.53
B47122	695.32	760.89		D04432	719.48	730.97
B47123	774.32	797.25		D06265	467.12	480.40
B47124	520.95	538.23		D06268	672.29	683.38
B75220	714.91	765.27		D06824	734.25	772.42
B76804	No data	No data		D12467	623.72	640.03
B76905	812.09	846.30		D12528	No data	No data
B81327	615.19	627.30		D19378	592.79	595.50
B83973	617.17	639.11		D25713	615.10	654.26
B87517	1277.10	1333.64		D26918	782.70	796.00
B87526	631.70	641.40		D28066	725.05	741.50
B87527	788.10	799.89		D36431	743.24	762.28
B90457	685.94	692.89		D41312	926.54	957.15
B96517	586.42	593.13		D43875	630.29	630.53
C03874	768.08	788.23		D76669	894.25	927.03
C04931	1016.50	1032.02		D76670	552.42	560.64
C04933	856.74	848.99		D79349	621.02	651.02
C04934	650.52	682.93		D84949	606.66	619.74
C08363	670.72	681.22		D91432	735.73	726.43
C13160	886.09	911.68		D94506	899.15	936.58
C16324	353.98	355.19		D94508	614.52	612.15
C16328	595.77	617.84		D94509	658.84	734.82
C16333	958.65	974.77		E12665	675.53	687.95
C21235	673.36	661.78		E14412	668.08	665.06
C30576	749.16	775.91		E25338	533.56	566.78

Appendix B: Figures

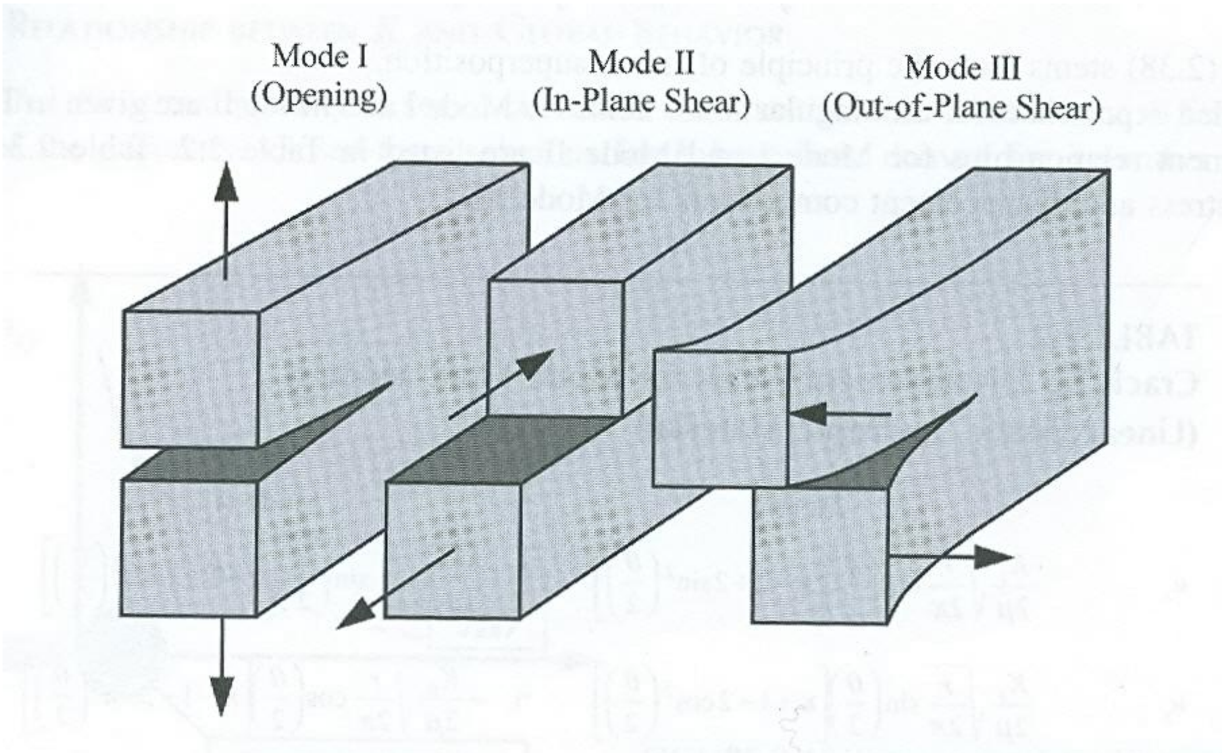


Figure 1: Schematic of three Fracture Modes

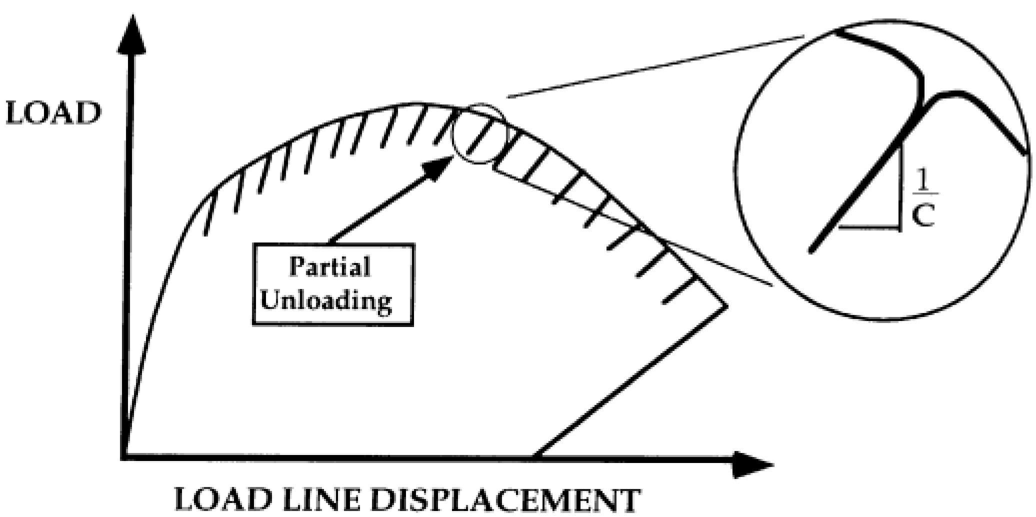
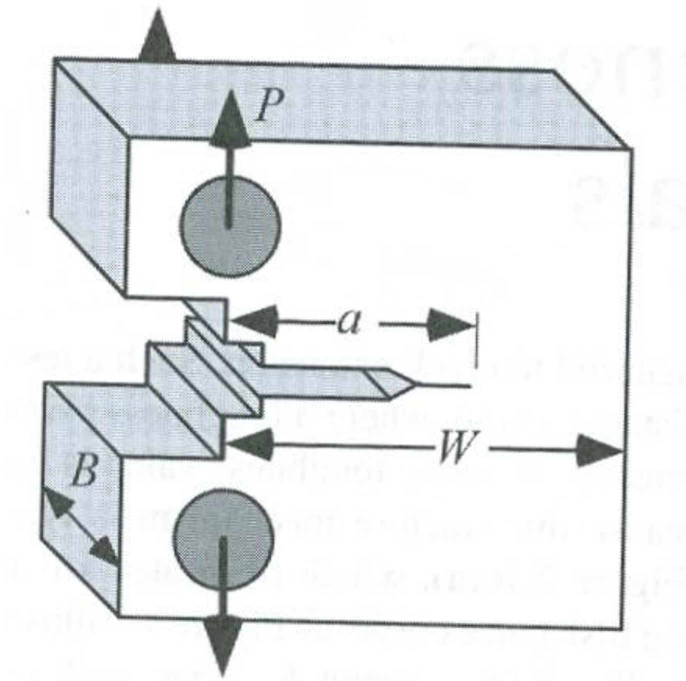
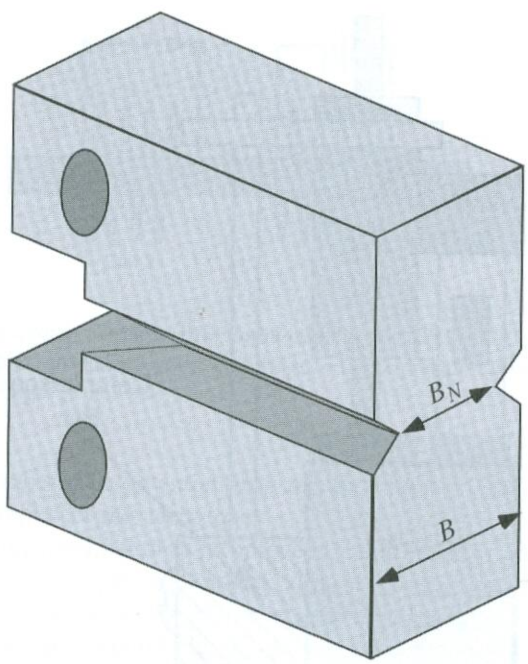


Figure 2: Schematic of J Load versus Displacement



Compact tension specimen



Sided grooved compact tension specimen

Figure 3: Specimen geometry showing smooth sided and side grooved

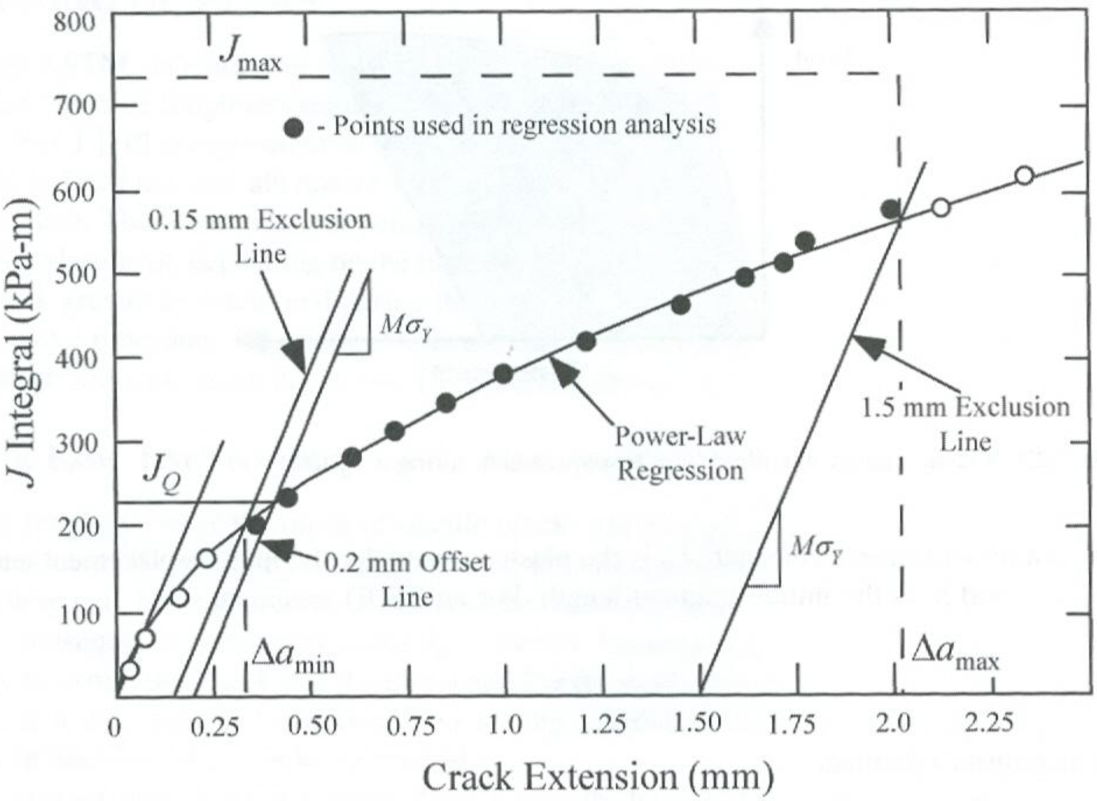


Figure 4: Schematic of the J-R curve construction procedure:

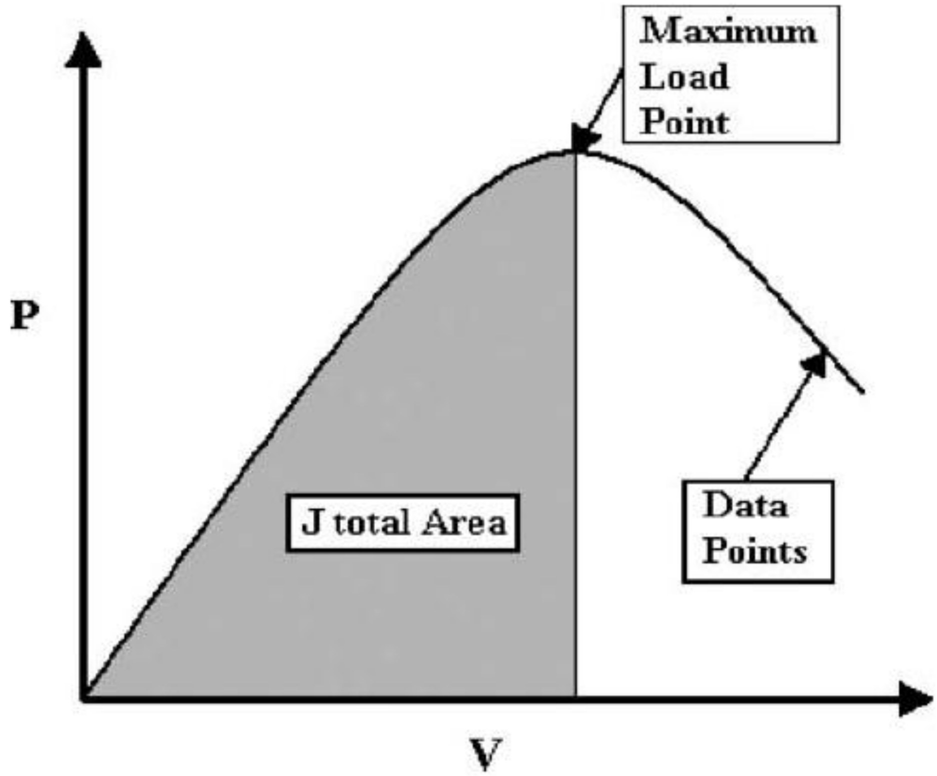


Figure 5: Definition of the J_{area} in the Landes-Pehrson method

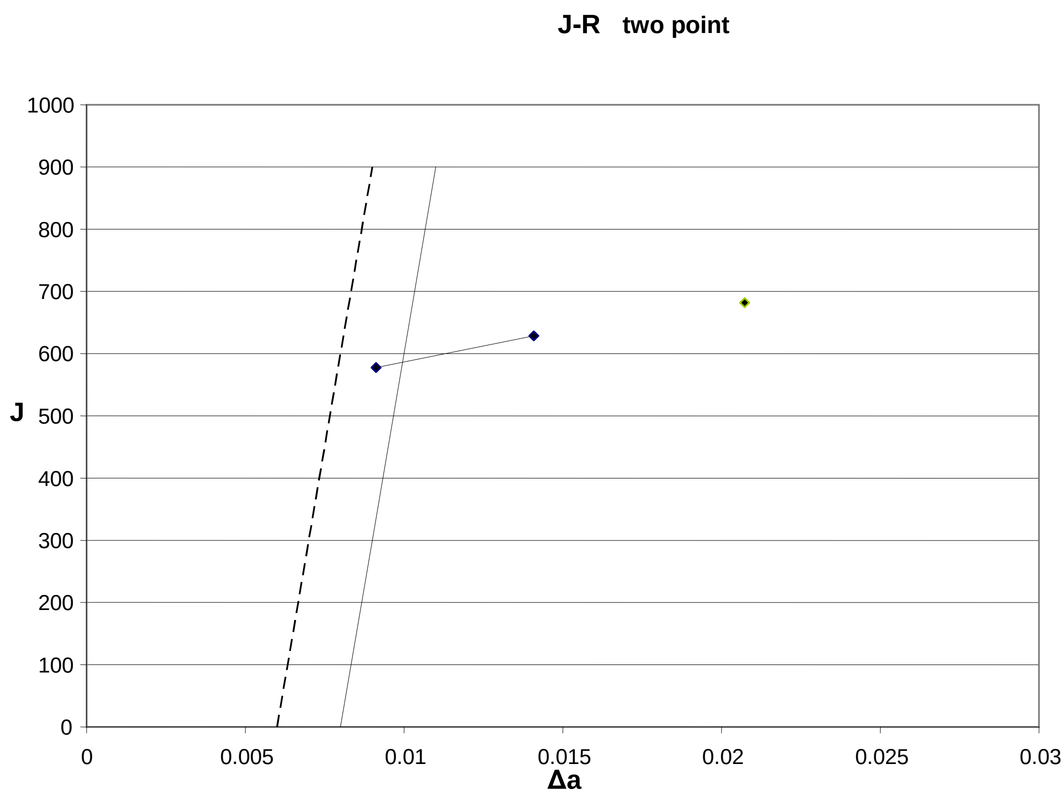


Figure 6: Example of the J-R two point method

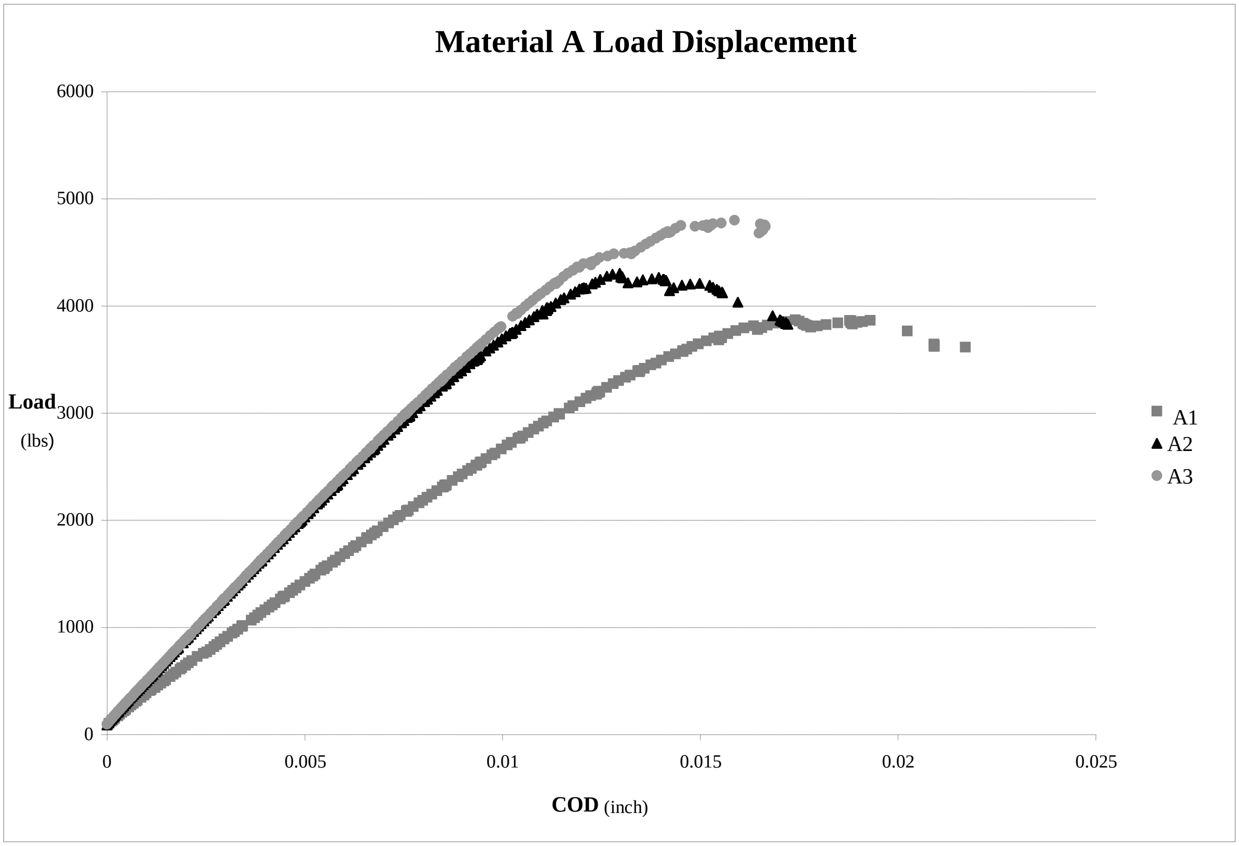


Figure 7: Three Example Tests from Material A Showing Load versus Displacement

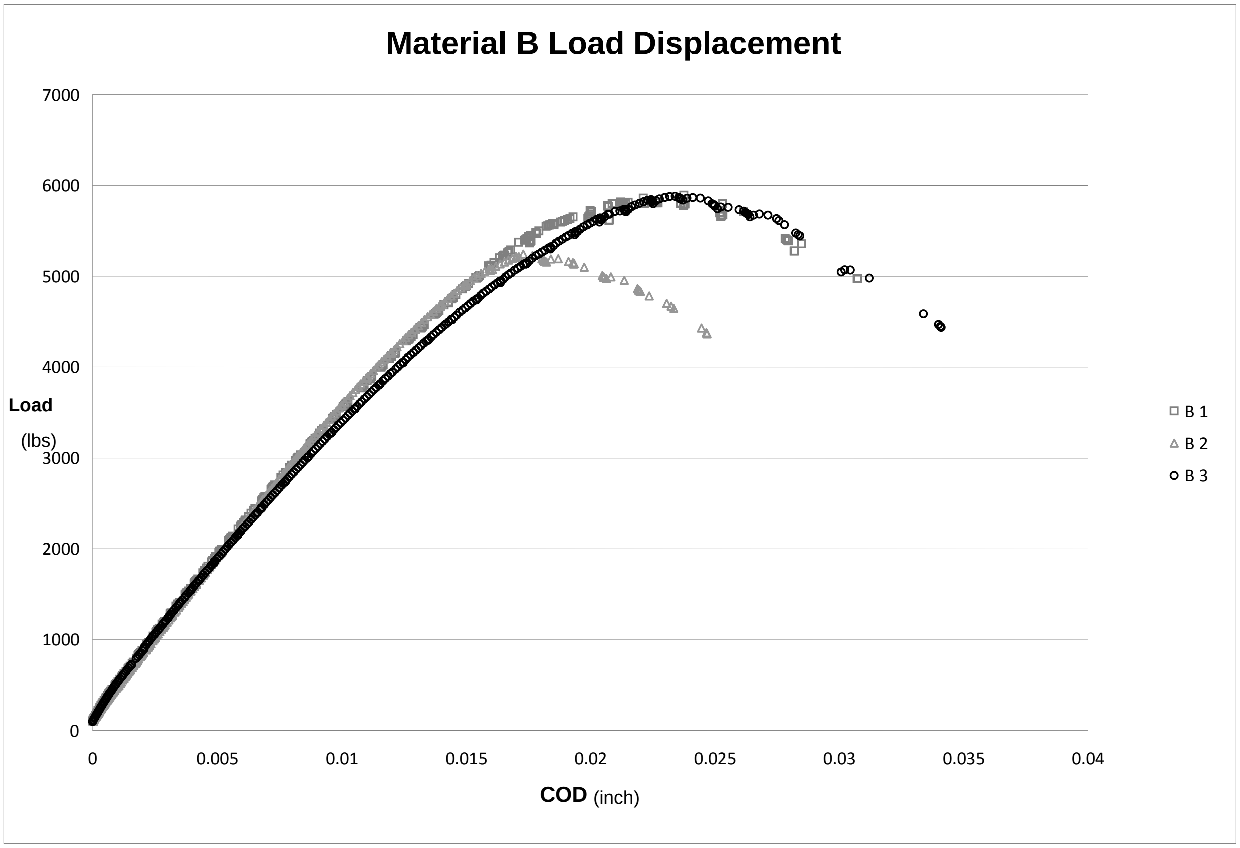


Figure 8: Three Example Tests from Material B showing load versus Displacement

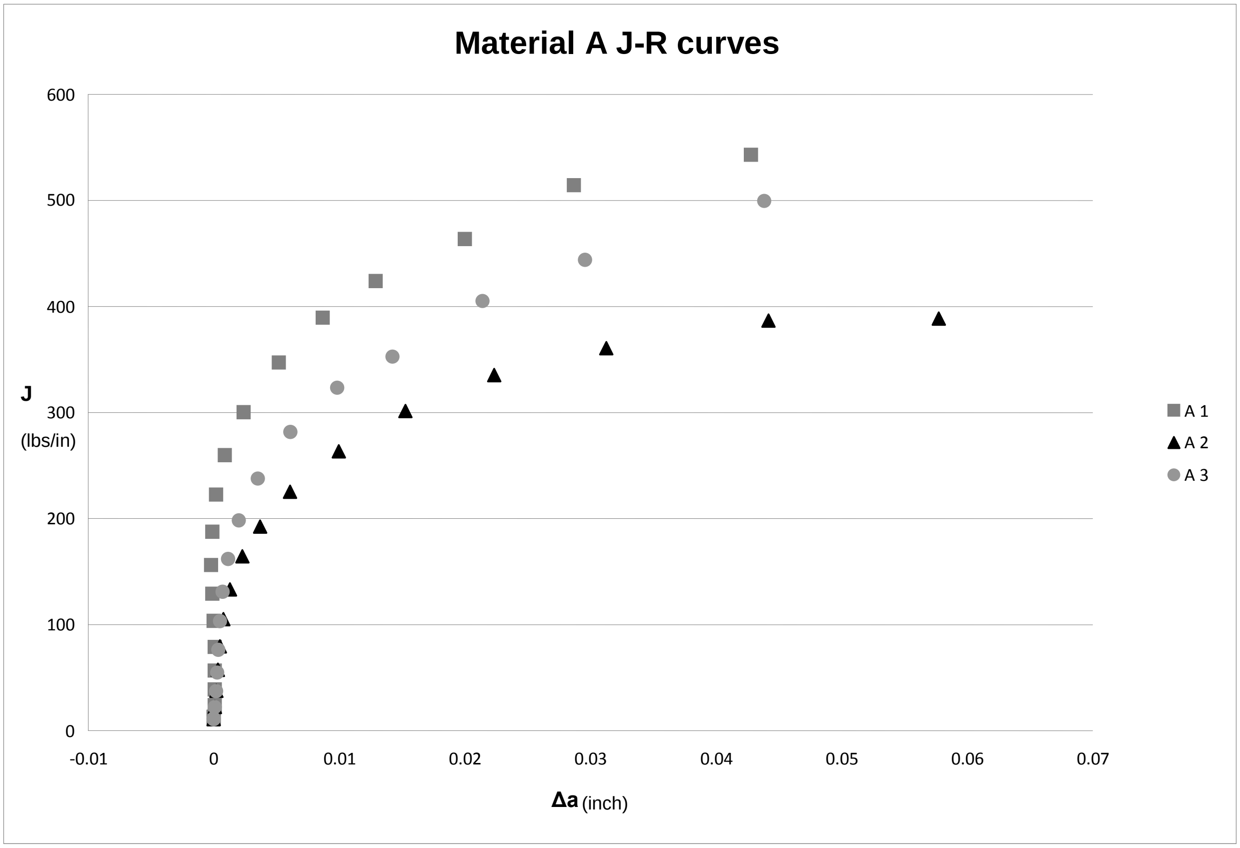


Figure 9: Three Example tests from Material A showing the J-R Curve

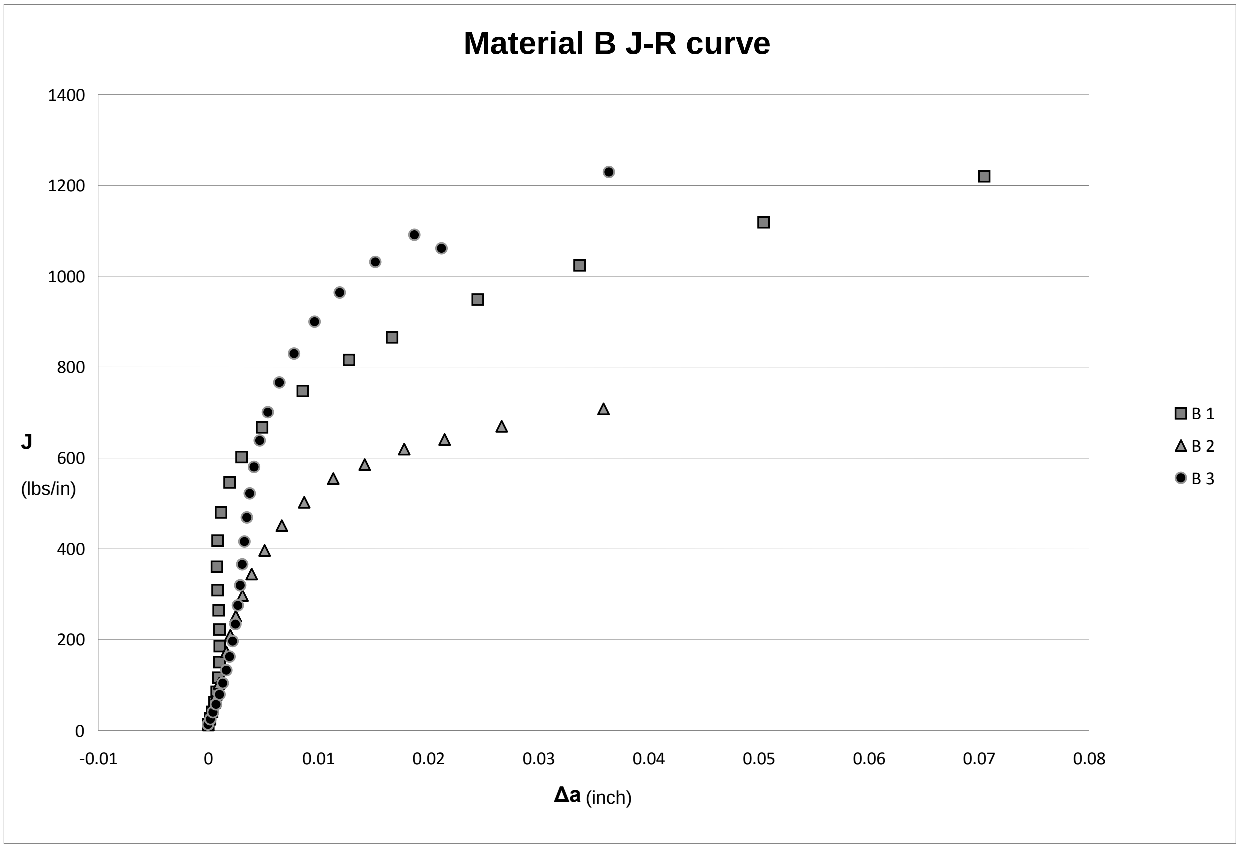


Figure 10: Three Example tests from Material B showing the J-R Curve

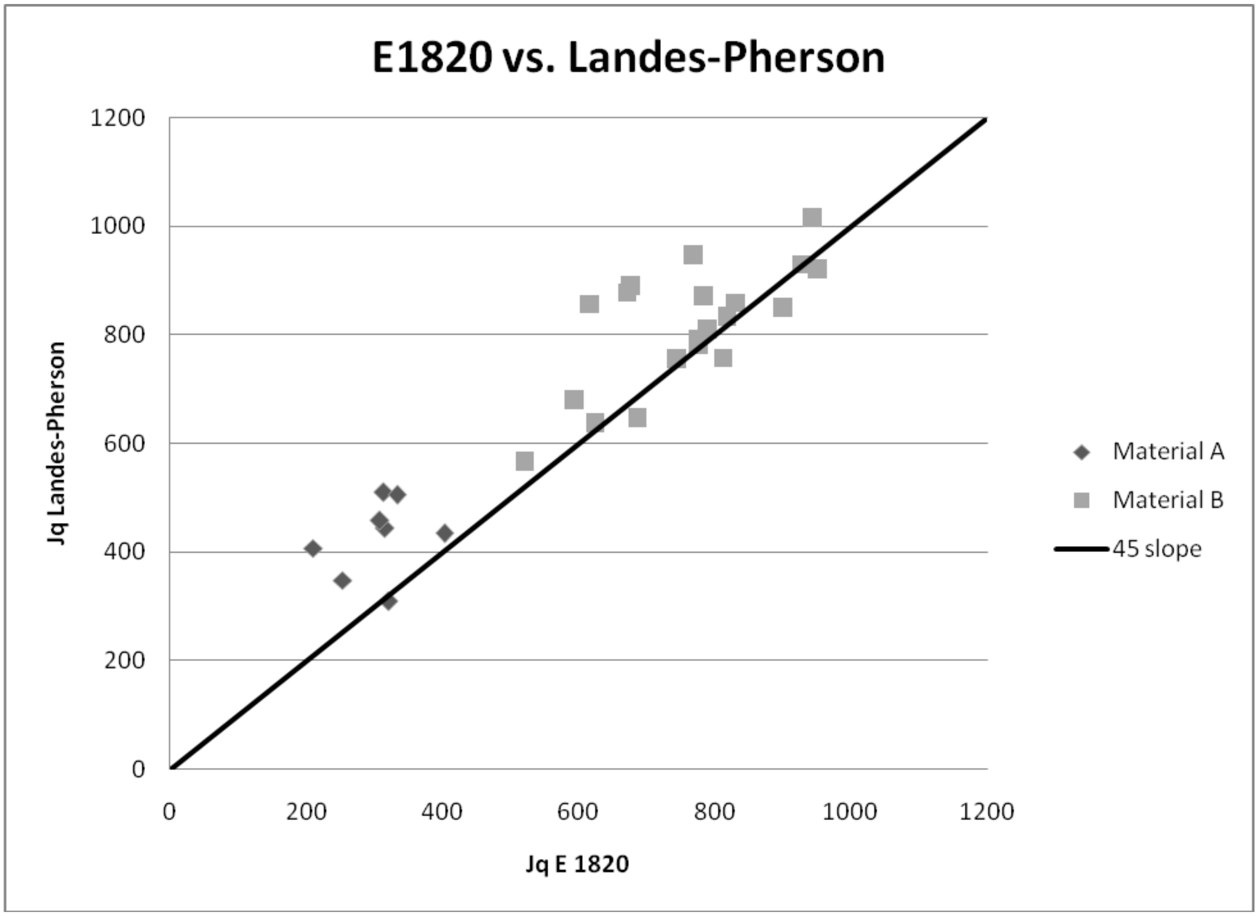


Figure 11: E1820 versus the Landes-Pehrson method for all valid tests

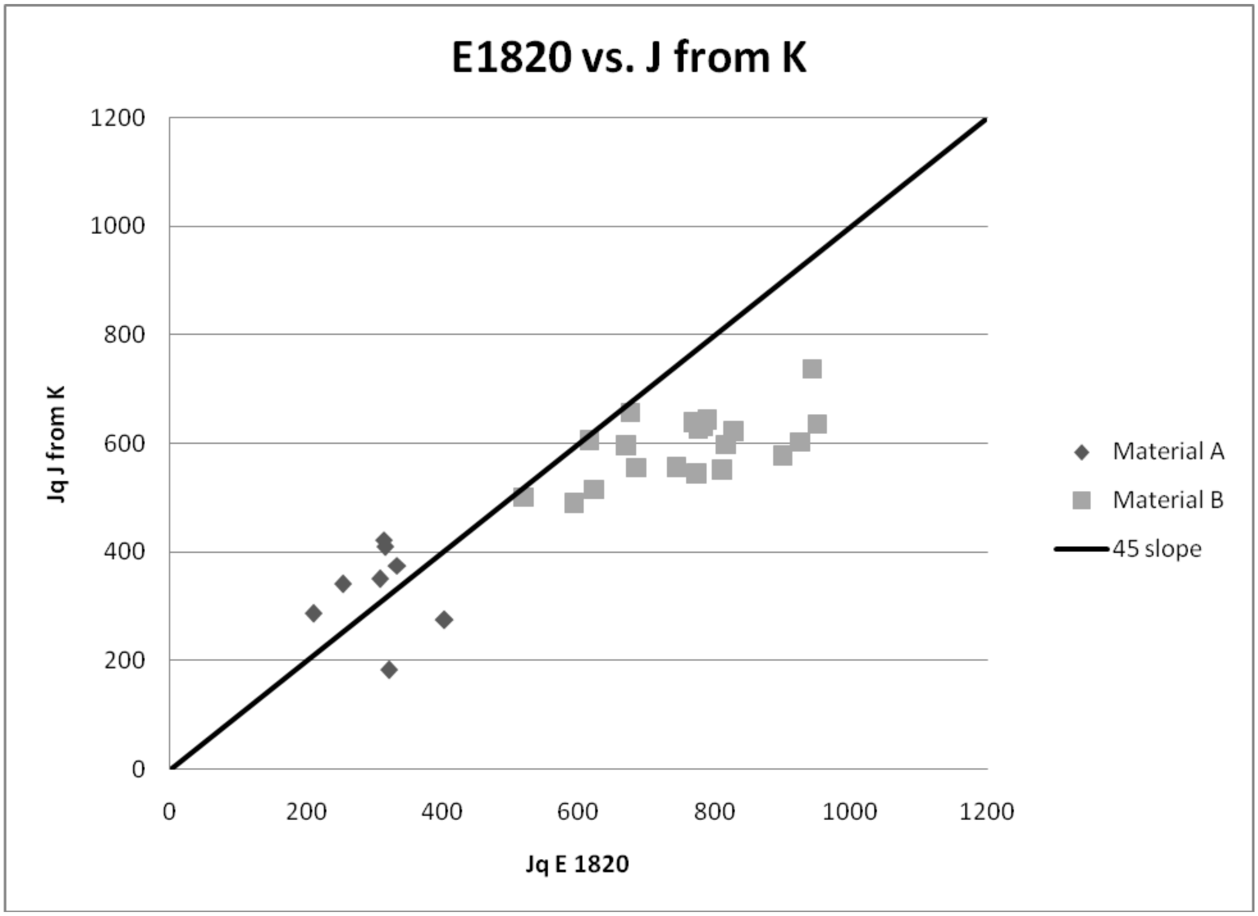


Figure 12: E1820 versus the J from K method for all valid tests

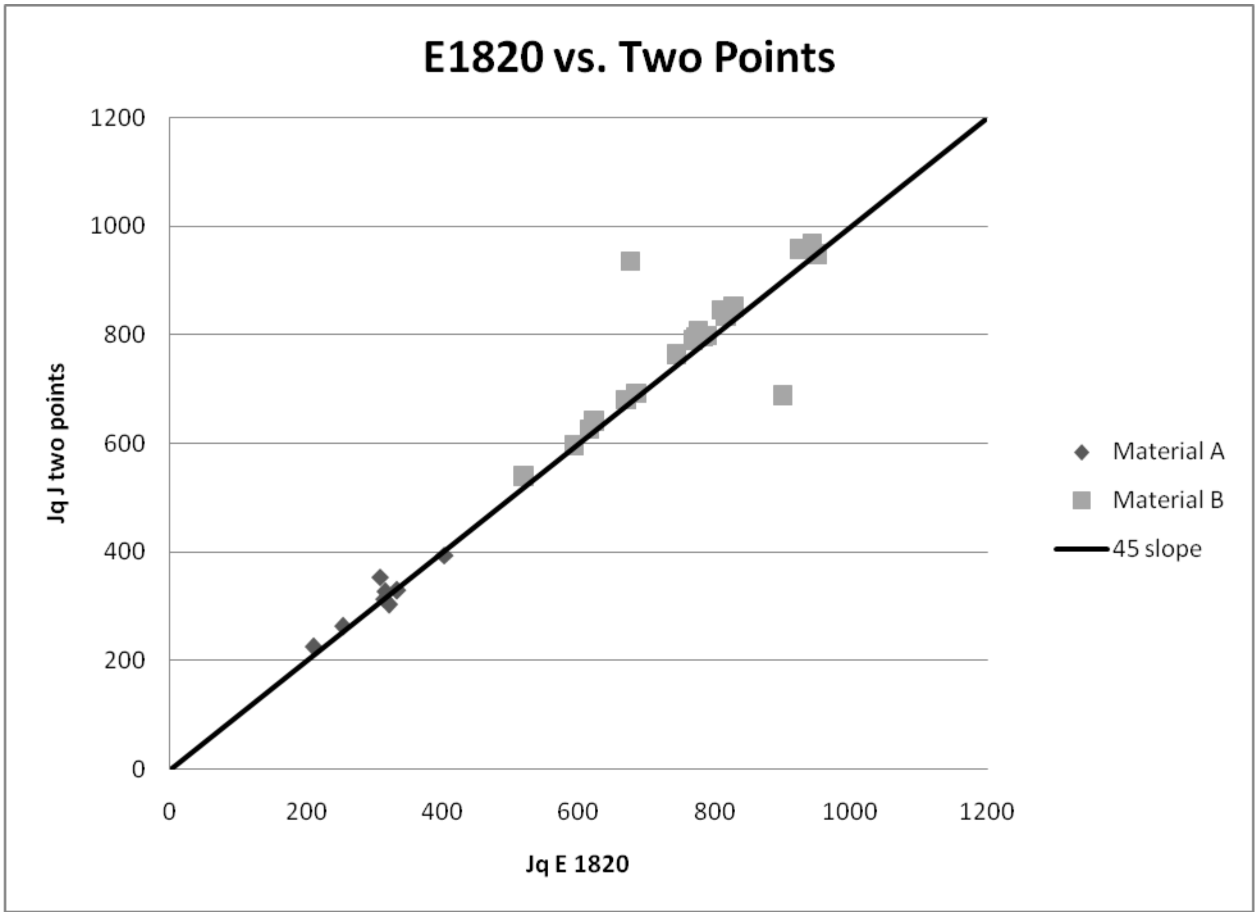


Figure 13: E1820 versus the Two Points method for all valid tests

Vita

Thomas Battiste was born on December 1, 1977, in Oak Ridge Tennessee. He graduated from Oak Ridge High School in 1996 and started at the University of Tennessee Knoxville. After taking time off to work, he returned and finished his degree in Mechanical Engineering in 2004. He then started graduate school while working at Oak Ridge National Laboratory until he acquired a graduate assistantship in the fall of 2007. The degree of Master of Science in Mechanical engineering will be awarded in May 2010.